Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 61 (2014) 2678 – 2681
Energy Procedia

The 6th International Conference on Applied Energy – ICAE2014

An Efficient Pulse Tube Cryocooler for BOG Recondensation in LNG Tanks

J. Y. Hu[a, b]*, J. Zhu[b], S. Chen[b], E. C. Luo[a, b], W. Dai[a, b], H. B. Li[a, b]

[a]*Key laboratory of Cryogenics, Technical Institute of Physics and Chemistry, CAS, Beijing, 100190*
[b]*Zhongke-Lihan Thermoacoustic Technologies Inc., Shenzhen 518055, China*

Abstract

Small liquid natural gas (LNG) distribution stations require compact, highly efficient cryocoolers to condense boil-off gas in the LNG tank. This paper reports a pulse tube cryocooler measuring 420*690*780 mm and weighing 180 kg. Using low input electric power, the relative Carnot efficiency was greater than 20%. Increasing the power to 11 kW, the cryocooler produced approximately 1.2 kW of cooling at 120 K. Approximately 293 normal cubic meters of boil-off NG per day can be condensed. If heat transfer in the main heat exchanger was improved, cooling power and efficiency could be improved. It presents a new efficient, compact and reliable configuration for the energy saving in LNG distribution stations.
Keywords: Pulse tube; Cryocooler; Liquid natural gas; Boil-off gas

1. Introduction

Natural gas (NG) is definitely a viable option in bridging our energy gap to the next century of renewable energy. It is recognized as a safe and environmental responsible fuel and has reduced emissions in many parts of the world. NG has being remained the fastest growing energy resource throughout the world for more than two decades. Many NG distribution stations will be built in the next few years [1]. Because of the substantial volume reduction, the condensed form of NG is considered to be a better way for these stations to store and transport the gas. The liquid NG (LNG) at about 120 K is stored in special tanks with well-insulated walls. Because of unavoidably heat transfer from the surroundings LNG is vaporized, which generates boil-off gas (BOG).

In large-scale terminals, BOG is compressed or recondensed using a portion of the cold LNG sendout or used as a fuel source [2]. In small-scale LNG distribution stations measuring of a few hundred cubic meters, the quantity of BOG produced is substantially lower. The NG exhaust is not always on, and there is not enough cooling power to ensure that BOG is continuously recovered. Conventional liquefaction processes such as cascade liquefaction, mixed refrigerant and expansion-based processes are too large to

* Corresponding author. Tel.: 86-10-82543733; fax: 86-10-62554670.
E-mail address: jyhu@mail.ipc.ac.cn or ecluo@mail.ipc.ac.cn.

Peer-review under responsibility of the Organizing Committee of ICAE2014
doi:10.1016/j.egypro.2014.12.275

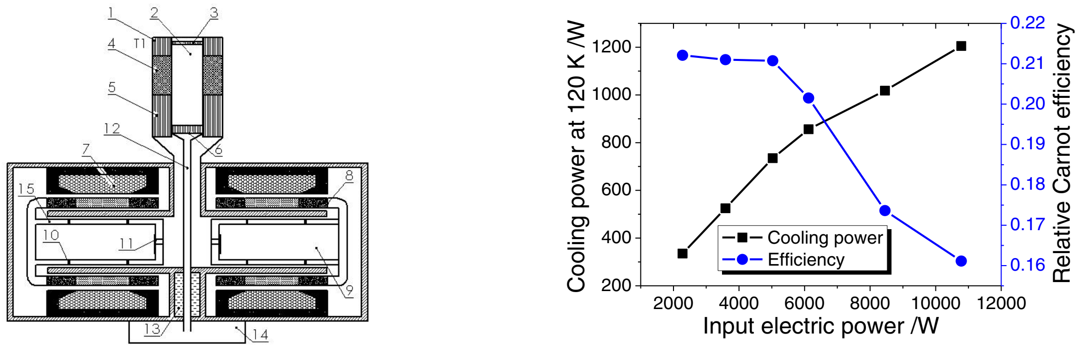
be compatible with small-scale LNG distribution stations. Thus, novel cryocoolers with a few kilowatt cooling capacities at 120 K are urgently desired for use in these stations.

Nomenclature

BOG	boil-off gas	LNG	liquid natural gas
NCM	normal cubic meter	NG	natural gas
I	current	Re	real part of
R_{mech}	mechanical resistance	v	velocity of piston
W_{piston}	acoustic power delivered by piston	τ	transduction coefficient
$\tilde{}$	complex conjugation	$\lvert\,\rvert$	complex modulus

Stirling type pulse tube cryocoolers are compact, long-lifetime cryocoolers with high efficiencies. They consist of mainly two parts: a linear compressor and a cold finger. In the linear compressor, electric power is converted into acoustic power. In the cold finger, the acoustic power is used to produce a refrigeration effect. Historically, the pulse tube cryocooler was developed to cool infrared detectors for aerospace and military applications. Their cooling capacity is often less than ten watts. Recently, the cooling capacity of the pulse tube cryocooler has increased to hundreds watts to cool some high temperature superconducting equipment [3]. This inspired us to design a pulse tube cryocooler to recondense BOG in small LNG distribution stations for the energy saving.

2. Theoretical Design



(a) (b)

Fig. 1 (a) Schematic of the pulse tube cryocooler, where 1 is the cold heat exchanger, 2 is the pulse tube, 3 is the flow straightener, 4 is the regenerator, 5 is the main heat exchanger, 6 is the secondary heat exchanger, 7 is the motor stator, 8 is the moving magnet, 9 is the reservoir in the piston, 10 is the orifice, 11 is the check valve, 12 is the inertance tube, 13 is the cooling water, 14 is the reservoir connected with the inertance tube, and 15 is the piston. (b) Dependence of the cooling power and efficiency on the electrical power.

The pulse tube cryocooler is regenerative. As shown in Fig. 1 (a), the high-pressure helium enclosed in the system is driven back and forth by the pistons. When the gas parcels are pushed forward to the cold heat exchanger, they expand and absorb heat from the cold heat exchanger. When the gas parcels are pulled back to the main heat exchanger, they are compressed and reject heat to the main heat exchanger. Thus, the NG is liquefied at the outside of the cold heat exchanger. Typical LNG is kept at temperature of about 120 K, so the designed temperature of the cold heat exchanger was set to this point in the experiment. The main heat exchanger was cooled using room temperature air or water

To liquefy BOG in the LNG tank, the cooling capacity of the pulse tube cryocooler should be on the order of kilowatts. With increasing cooling capacity, the length-to-diameter ratios (L/D ratio) of the regenerator and the pulse tube decrease. Because of the great temperature gradient along the axis, the temperature distribution on the cross-section is very easy to become inhomogeneous. The coupling of the temperature inhomogeneity and the flow admixes the working gas of different temperatures and deteriorates the cooling performance severely. According to our numerical simulation, the optimum length of the regenerator was approximately 60 mm [3]. The outer diameter of the regenerator was 120 mm and the corresponding L/D ratio was only 0.5. To increase the L/D ratio and suppress the possible inhomogeneity, the regenerator was lengthened to 75 mm. The length of the pulse tube was generally less than 90 mm in small capacity pulse tube cryocoolers. Here it was lengthened to 155 mm.

The size of a typical pulse tube cryocooler is dominated by the size of the linear compressor. To make it easy for the pulse tube cryocooler to couple with the LNG tank, it is necessary to minimize the size and weight of the compressor. The acoustic power delivered by the piston W_{piston} can be expressed as [4]

$$W_{piston} = 0.5\mathrm{Re}(\tau I v) - 0.5R_{mech}\left|v\right|^2 \quad (1)$$

Where the two terms at the right side of Eq. (1) represent the electro-magnetic power and mechanical power dissipated by mechanical resistance. The electro-magnetic force τI could be less if the piston moved at a higher velocity. Less electro-magnetic force requires less magnetic material and thin copper wire which would effectively decrease the diameter of the compressor. But higher velocity piston movements will also introduce more mechanical dissipation. The only way to solve this problem is to decrease the mechanic resistance. The mechanical resistance is influenced by the gap between the piston and the cylinder. Smaller gap means lower resistance. For a piston in diameter of 120 mm suspended by Oxford springs, the gap is generally more than 2×10^{-5} m, otherwise it is very difficult to avoid the friction between the piston and the cylinder.

Here gas-bearing pistons were used to minimize the overall size as shown in Fig. 1 (a). On the compression surface of the piston, there is a check valve. When the gas in the compression chamber is compressed during each cycle, a small portion of the gas flows into the internal reservoir of the piston and raises the average pressure in the internal reservoir above the pressure outside. The gas is then driven to the gap between the piston and cylinder through orifices to suspend the piston. Using the gas-bearing pistons, the gap can be decrease to 1×10^{-5} m or less, and the Oxford springs used in traditional linear compressors are eliminated, allowing the displacement of the piston to be increased.

3. Experimental Setup and Results

A schematic of the experimental setup is presented in Figure 1 (a). The parameters of the cold finger were the same as those reported in Section 2. With the gas-bearing pistons, the measured mechanical resistance was only 40 kg/s, indicating that the piston's diameter could be as little as 118 mm. The diameter and length of the compressor were 420 and 690 mm, respectively. The total height and mass of the cryocooler were 780 mm and 180 kg, respectively. The main heat exchanger was cooled by water at 293 K. Because hundreds of watts of acoustic power were dissipated in the inertance tube, the inertance tube was also cooled using water. The temperature of the cold heat exchanger was measured using Pt-100 resistance thermometers. The gas temperature between the main heat exchanger and the compressor was also measure using an armored thermocouple. Five constantan wires heated using a direct-voltage source were mounted on the cold tip to simulate the heating load. The input electrical power was calculated using the voltage and current data acquired through a program based on Labview 7.1.

Fig. 1 (b) presents the electrical power dependence of the cooling power and relative Carnot efficiency at cooling temperature of 120 K. The working frequency of the compressor was 46 Hz. The charging pressure was 2.8 MPa. It is apparent that the efficiency was higher than 20% when the input electrical power was less than 6 kW. If the latent heat of vaporization is 494kJ/kg, the electrical energy required for recondensing BOG was 1227.9 kJ per normal cubic meter (NCM). If the electrical energy was generated by burning NG and the efficiency was 30%, it would only consume 0.21 NCM NG. With the input electric power increased to 11 kW, the cryocooler can produce 1.2 kW cooling power at 120 K. This means that 293 NCM boil-off NG can be condensed per day.

From Fig. 1 (b), there was a drop in efficiency when the electric power was higher than 5 kW. This may be because of imperfect heat transfer between the working gas and the wall in the main heat exchanger. When the electrical power increased to 11 kW, the gas temperature measured by the armored thermocouple was about 360 K which is much higher than that of the cooling water. If the heat transfer can be improved, the efficiency would also be improved.

4. Conclusion

This paper designed a pulse tube cryocooler to meet the need of small LNG distribution stations. In the design, the regenerator and pulse tube are lengthened to avoid possible temperature inhomogeneity. Gas-bearing pistons are employed to decrease the compressor size. In experiment, the cryocooler offers about 1 kW cooling power at 120 K. The maximum relative Carnot efficiency could be as high as 17.4%. The total weight of the cryocooler is only about 180 kg. It presents a new efficient, compact and reliable configuration for the energy saving in LNG distribution stations.

Acknowledgements

This work is supported by the Natural Sciences Foundation of China (No. 51276187), Joint Funds of NSFC-Yunnan (No. U1137606) and the National Basic Research Program (No. 2010CB227303).

References

[1] Li Y, Chen X, Chein M. Flexible and cost-effective optimization of BOG recondensation process at LNG receiving terminals. *Chem Eng Res Des*. 2012; 90: 1500-5.

[2] Mokhatab S, Mak JY, Valappil JV, Wood D. *Handbook of Liquefied Natural Gas*. 1st ed. Oxford: Gulf Professional Publishing; 2013.

[3] Hu JY, Zhang LM, Zhu J, Chen S, Luo EC, Dai W, et al. A high-efficiency coaxial pulse tube cryocooler with 500 W cooling capacity at 80 K. submitted to *cryogenics* 2014.

[4] Hu JY, Luo EC, Zhang LM, Wang XT, Dai W. A double-acting thermoacoustic cryocooler for high temperature superconducting electric power grids. *Appl Energ* 2013; 112: 1166-70.

[5] Beale WT, Unger RZ, van der Walt NR. Fluid bearing with compliant linkage for centering reciprocating bodies. US Patent, US 5525845 A. 1994.

Biography

Dr. Hu achieved his doctor's degree at Chinese Academy of Sciences in 2007. Then he has been working in Technical Institute of Chemistry and Physics of CAS. He was selected as the member of Youth Innovation Promotion Association of CAS and New-Star of Science and Technology of Beijing. Now he is an associated professor majors in the energy conversion in oscillating flow system.